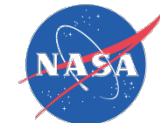


# CMC Combustor Liner Development within NASA's Environmentally Responsible Aviation Project

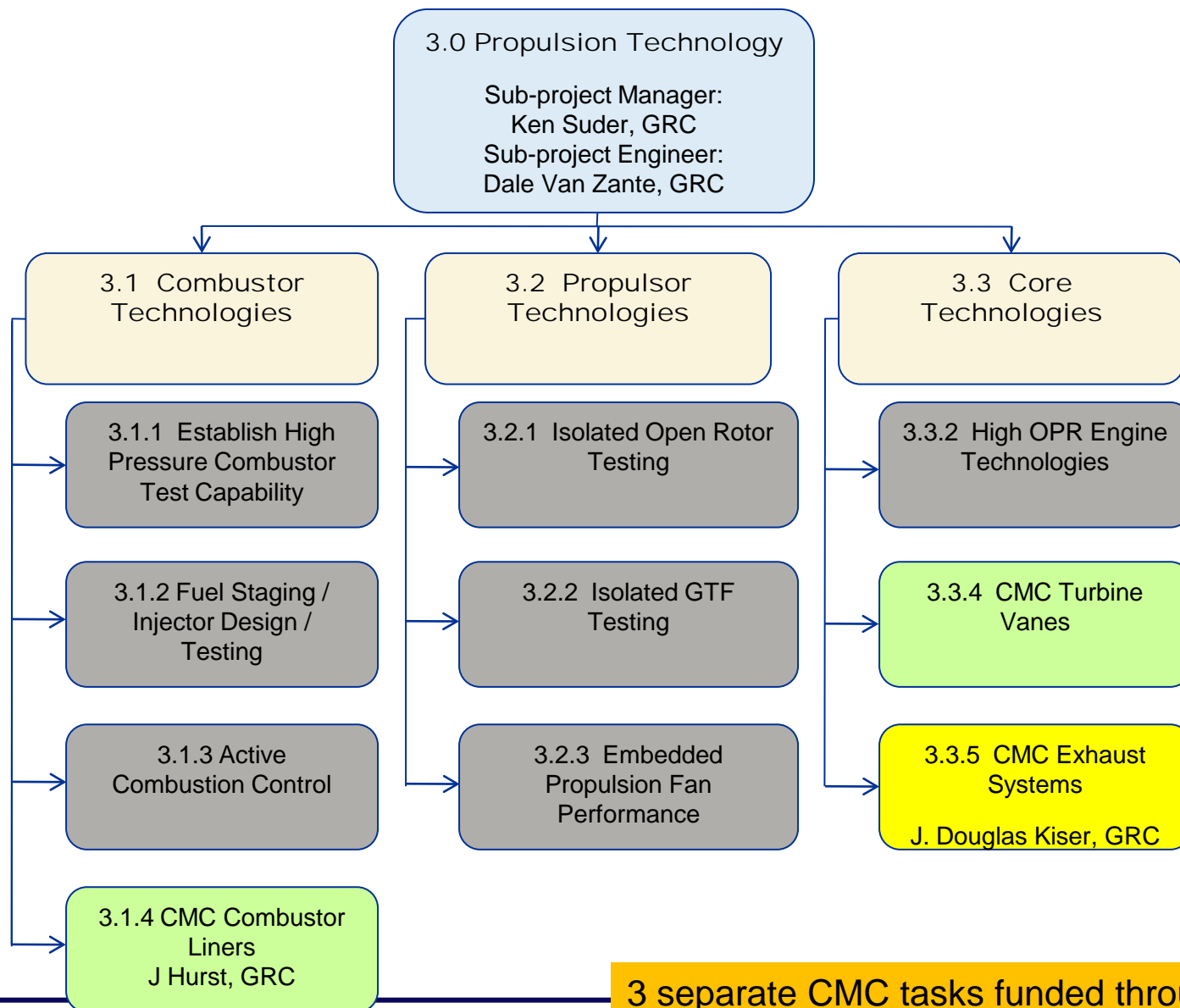
J. Hurst, D. Zhu, R. Bhatt  
NASA Glenn Research Center  
Cleveland OH



36th Annual Conference on Composites, Materials, and Structures.  
January 23 - 26, 2012



# ERA Propulsion Technology Tasks



3 separate CMC tasks funded through FY12 - 2

## NASA Environmentally Responsible Aviation (ERA) Program: SiC/SiC CMC combustor technology demonstrations in engine tests

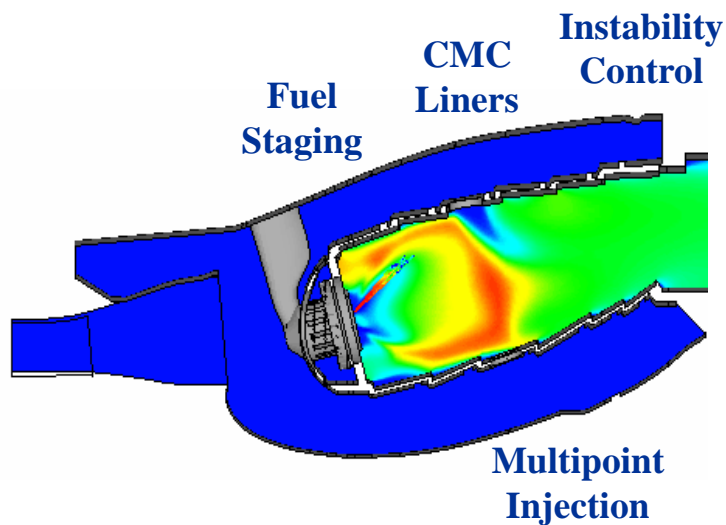
- N+2 generation (2020-2025) with 2400°F CMCs/2700°F EBCs (cooled)

ERA goals require  $\frac{1}{2}$  NO<sub>x</sub> of GENx

- GENx on 787 produces  $\frac{1}{2}$  the NO<sub>x</sub> of previous engines (GE 90 is on 777)

More and more lean –

- stealing air from cooling the liner and putting it through the injector
- Cooling air split : (liner/injector)  
70/30 - 777      20/80 – ERA



NRA Partners –  
GE Aviation      Pratt & Whitney

# ERA -CMC Combustor Liner Task

## Objective :

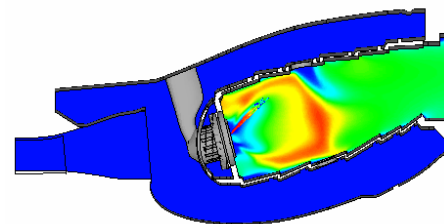
- Provide a “head start” to a potential ERA CMC combustor liner by investigating generic materials issues. Among those anticipated are fabricability, durability, CMC integration within an engine and advanced coatings. This may include attachment design, cooling holes, joining and repairability issues.
- Provide an independent assessment of a downselected CMC for fabricability and property capability.
- Create a roadmap to a CMC combustor liner, from currently available commercial material to an advanced CMC system with potential improvements to fiber architecture, matrix composition and ebc.

### Past Efforts - EPM

*EPM - Demonstrated ~9000-hour life at 2200 F in laboratory test cycles typical of aircraft engines - NASA GRC*



**Current Effort - ERA –N+2 generation (2020-2400°F CMCs/2700°F EBCs (cooled))**





## ERA -CMC Combustor Liner Task

**Objectives:** Investigate CMC combustor liner materials, identify issues challenging CMC incorporation into engines, mitigate issues as possible. Provide an independent assessment.

**Initial Task - Create a road map Issues for CMC Liner,**  
**Identify issues for CMC combustor liner –**  
series of meetings were held with engine companies identifying the top 3 issues –

**1. Durability – Insufficient data – both long term coupon and relevant engine environment**

*Mitigation –*

- ✓ *In-house durability testing, coupon creep/fatigue/etc testing,*
- ✓ *more realistic test facilities -*
  - *Biaxial ring-on-ring, laser high heat flux*
  - *Improvements to HPBR with hot cooling air, increase pressure to 16 atm, impingement and film cooling)*
  - *Subcomponent testing in HPBR and ASCR.*



## 2. Advanced Coatings –

### Improved coating compositions

(higher temperature, non-Si bond coats, non erosion, spallation, repairability)

#### *Mitigation -*

- ✓ *In-house research on advanced coatings – several vendors+in-house*
- ✓ *HPBR investigations.*
- ✓ *( Repairability effort delayed.)*

## 3. Engine Integration Issues –

CMC Attachment design & fretting coatings

Metal wear /vibratory environment

Chemical interactions at high temp - SRW

Joining flat to curved shapes/ thermal expansion mismatch -SRW

#### *Mitigation -*

- ✓ ~~NRA for attachment design,~~
- ✓ *in-house investigation into fretting coatings,*
- ✓ *rehab high temp fretting rig, various materials,*
- ✓ *SDL facility – delayed due to funding*



# ERA CMC LINER -

## *Phase 1 ERA – “Head Start”*

## *Phase 2 ERA -*

### **FY10 –**

- **Planned task with engine company input.**
- **Identified issues for liner development.**
- **Downselected CMC liner material based on fabricability, durability, TRL level 5-6.**
- **New testing capability developed**

### **FY13 – Subcomponent testing - ?**

### **Selected Technology Demonstration**

### **FY11 -**

- **Investigation of basic durability for coupons, creep, recession, effect of holes, etc**
- **Develop advanced high temperature coatings for liner surface operating temperatures up to 2800F and up to 60 OPR. Non-Si bond coat layers.**

### **Selected baseline material –**

**HiPerComp Gen 2 – 2D prepreg laminate Hi-Nic-S,  $V_f \sim 0.26$ , symmetric, balanced, 8 ply**

### **FY12 –**

- **Test subcomponents in simulated engine environment.**
- **CMAS modeling**

## ***End of Phase 1 ERA***

CMC combustor liners offer such benefits as higher temperature operation, reduced cooling, lighter weight, and reduced NOx emissions compared to current metallic based combustors.

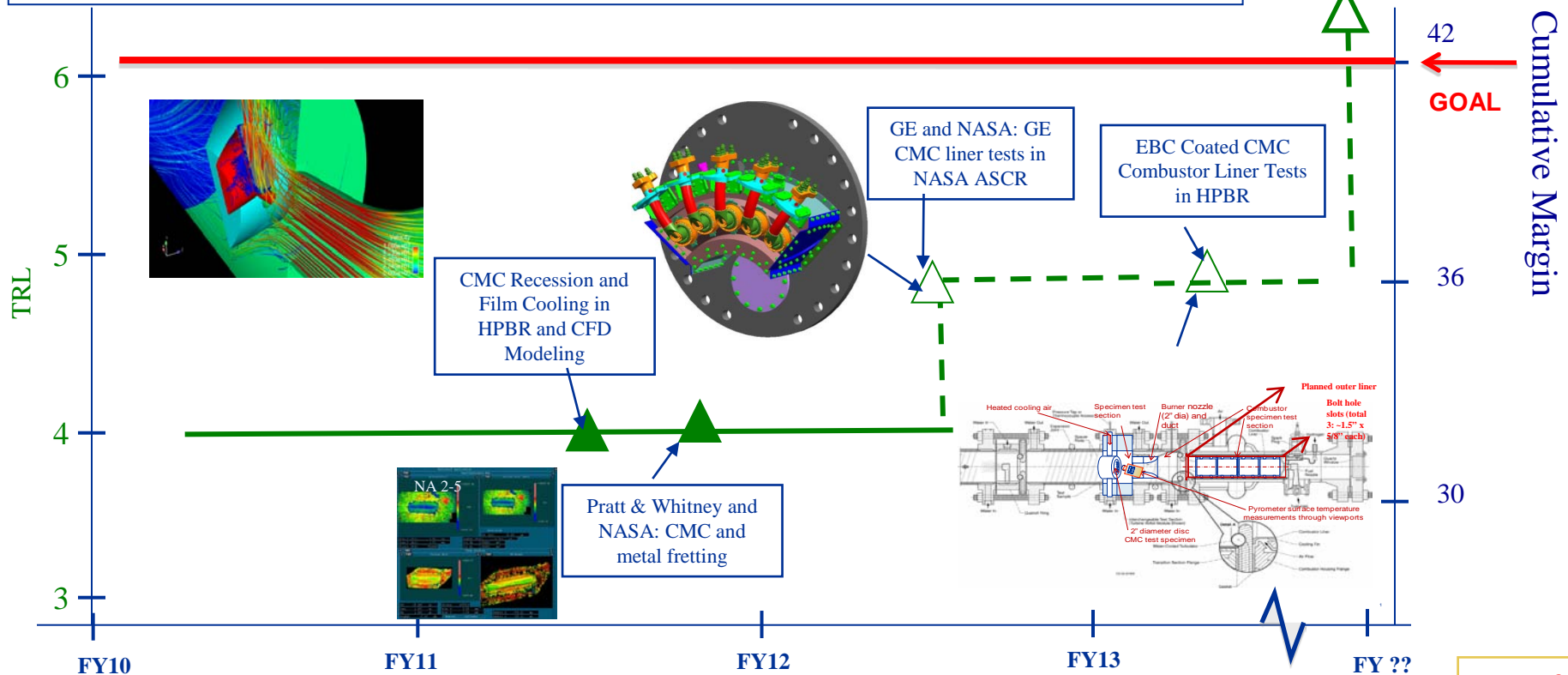
**The Goal is a durable EBC/CMC combustor liner system operating at 2700° F and 60 atm.**

One system study stated that the use of a CMC liner instead of a current metallic would translate to a 60% reduction in cooling and a 40% reduction in NOx.

The CMC combustor technology could be used in high by-pass ratio engines.

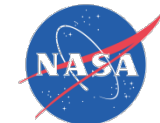
EBC coatings are prepared at a variety of vendors and NASA GRC

Goal could be achieved with long duration tests at 60 atm and 2700°F temperature





# 03.01.04 CMC Combustor Liner– Roadmap



## Combustor Technologies ERA.03

Combustor Relevant Test dev

CMC Liner Subcomponent Testing

### 03.01.04.1 CMC Durability

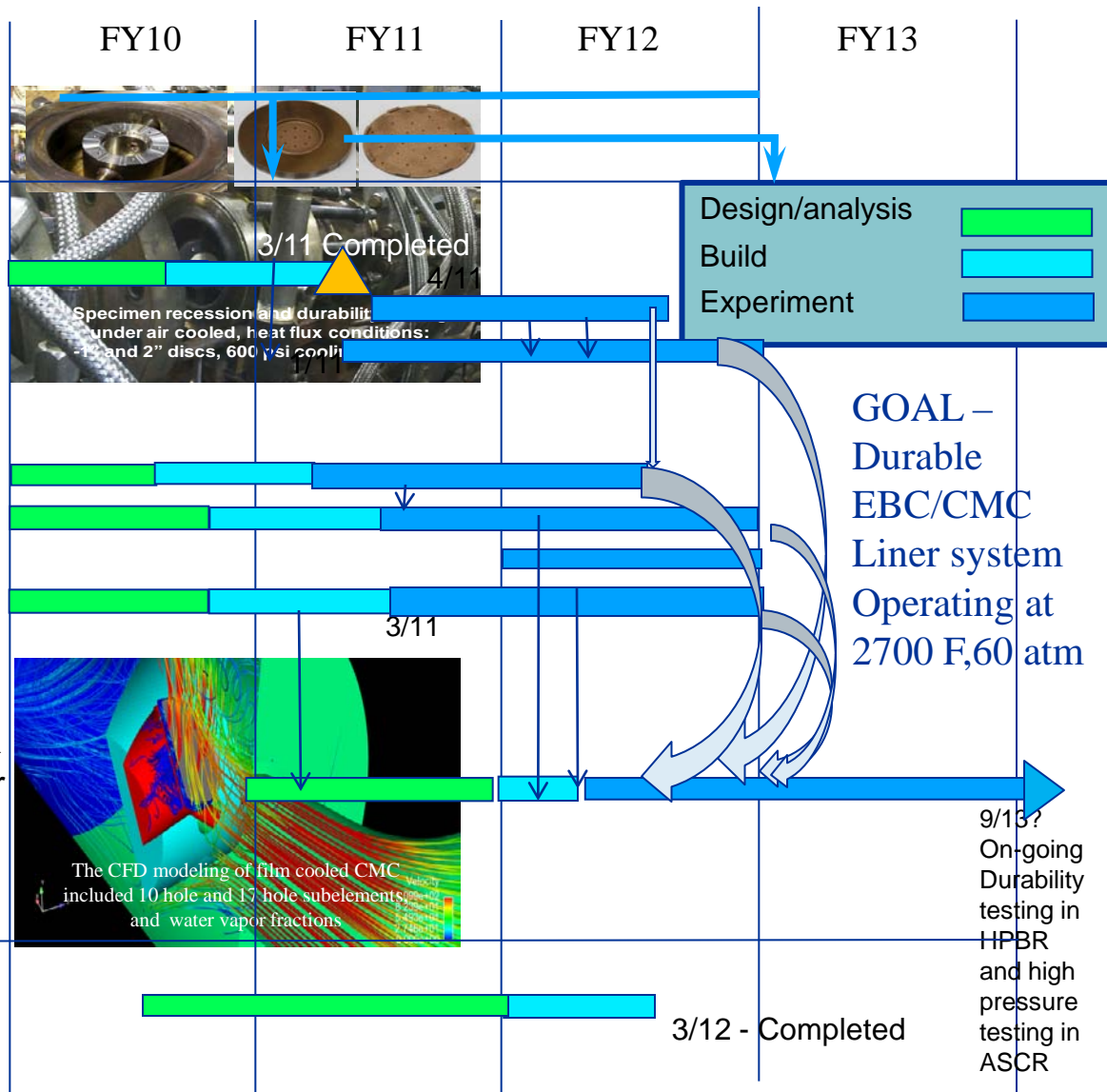
- Relevant comb test dev
- Recess Model dev
- Data base development /effect of holes

### 03.01.04.2 Environmental barrier coatings

- Advanced bond coats dev
- Adv coating system dev
- CMAS model dev
- HPBR – mods :inc press, warm cooling air

### 03.01.04.3 Subcomponent testing in HPBR subcomponent -combustor liner

### 03.01.04.04 Fuel Modulation



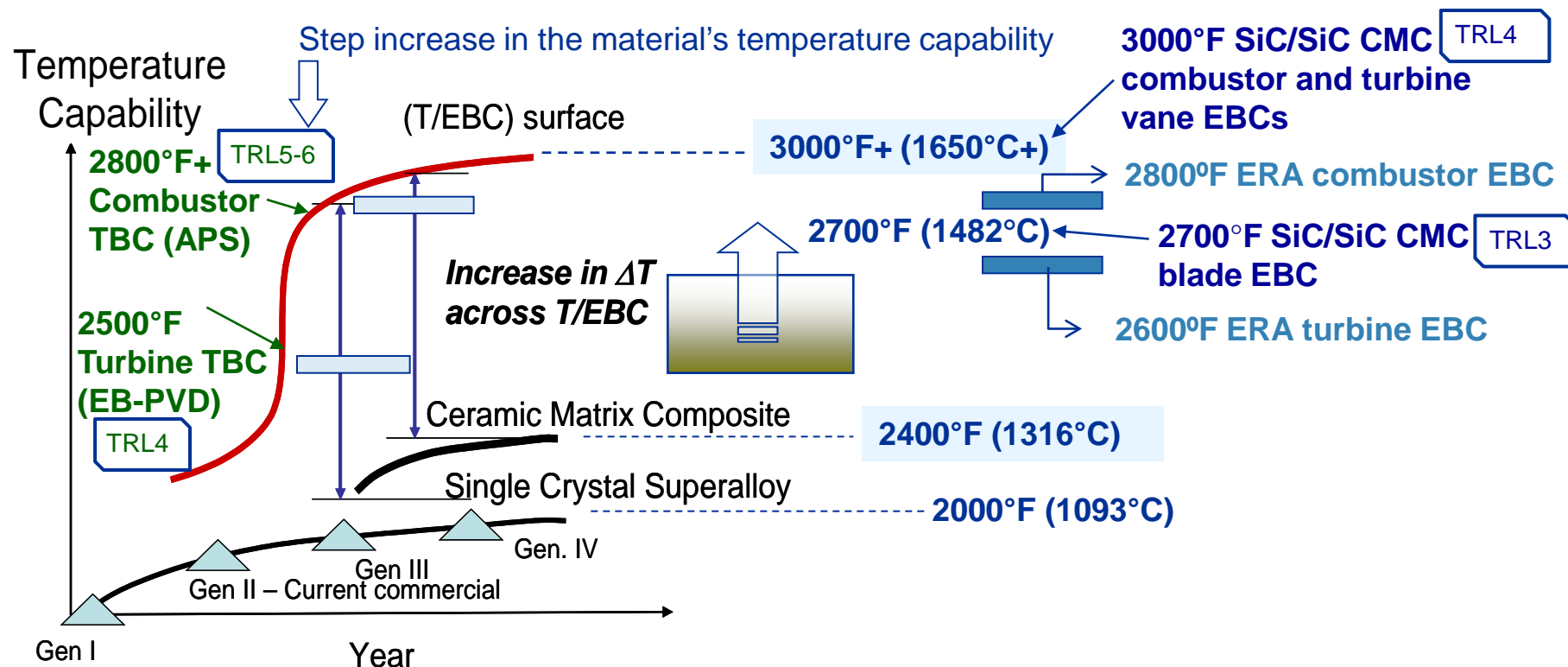


# The Environmental Barrier Coating - CMC Component Development and Temperature Goals

## — Ceramic coating system development goals

- Meet engine temperature, performance and durability requirements
- Help fundamental understanding, database and design tool development
- Increase the coating Technology Readiness Levels

ERA: an excellent opportunity to demonstrate and transition the technologies





## ERA CMC Liner Initial Test Matrix 1

## Creep - Tensile

Description	Load	Temp1	Temp2	Temp3	Temp4	total
0/90		2200 F	2400	2700	3000	
	15 ksi	3	3	3	3	12
	20 ksi	2	3	3	2	8
	10 ksi	2	3	3	2	8
45/45, 20/70, 70/20	15 ksi	1	2	2		5
	20 ksi	1	2	2		5
<del>0/0 Deleted</del>	<del>15 ksi</del>	<del>1</del>	<del>3</del>	<del>3</del>	<del>1</del>	<del>8</del>
	<del>20 ksi</del>	<del>1</del>	<del>3</del>	<del>3</del>	<del>1</del>	<del>8</del>
	<del>10 ksi</del>	<del>1</del>	<del>3</del>	<del>3</del>	<del>1</del>	<del>8</del>

## Creep - compressive

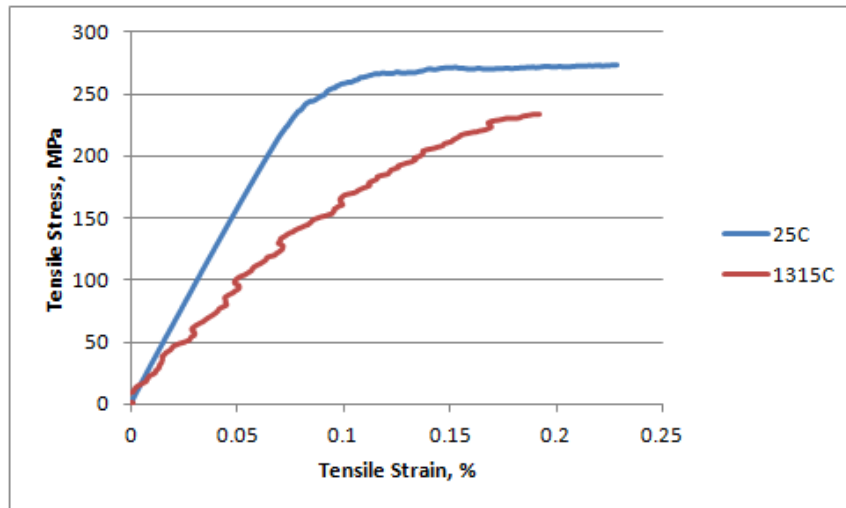
0/90	15	2	Additional Test Matrices for Fatigue			
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## FF -

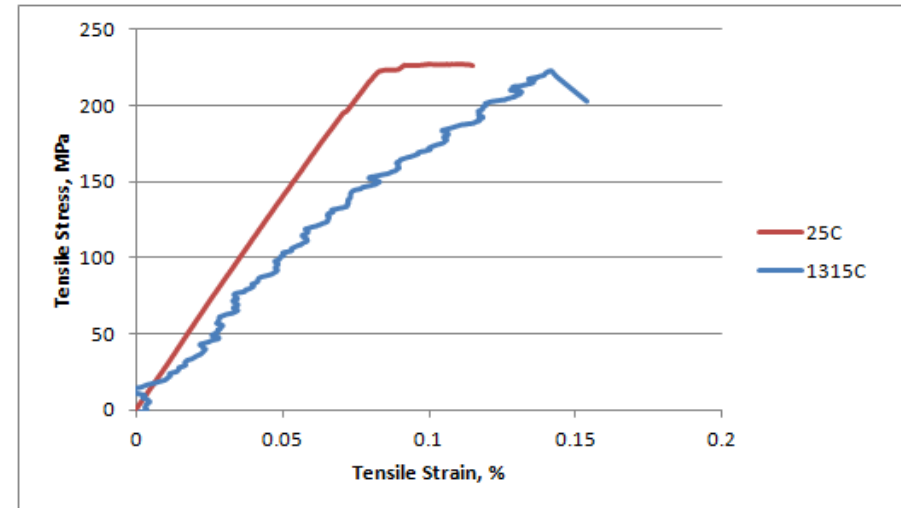
0/90 RT	3 RT	1	2	2	1	6
45/45, 20/70, 70/20	3 RT	1	2	2	1	6
<del>0</del>	<del>3 RT</del>	<del>1</del>	<del>2</del>	<del>2</del>	<del>1</del>	<del>6</del>

## Tensile Stress-Strain Behaviors ( $V_f \sim 0.26$ ) Tested in Air

### 0/90 Laminates

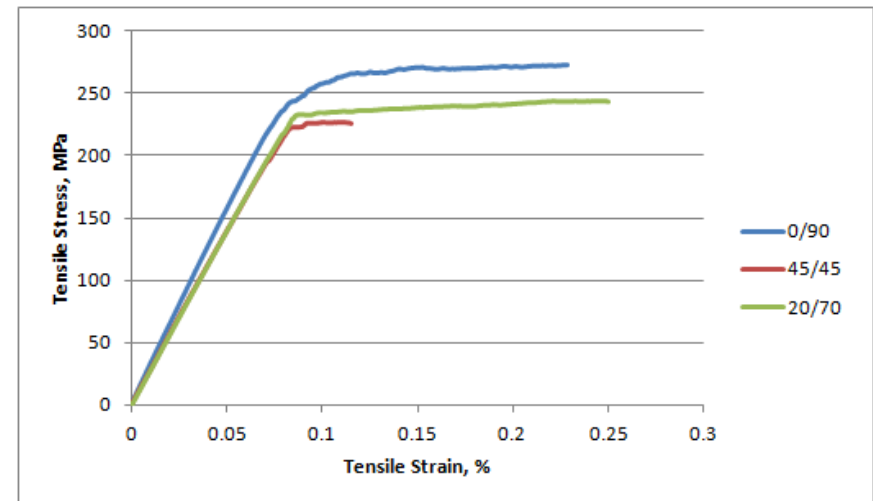


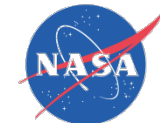
### +45/-45 Laminates



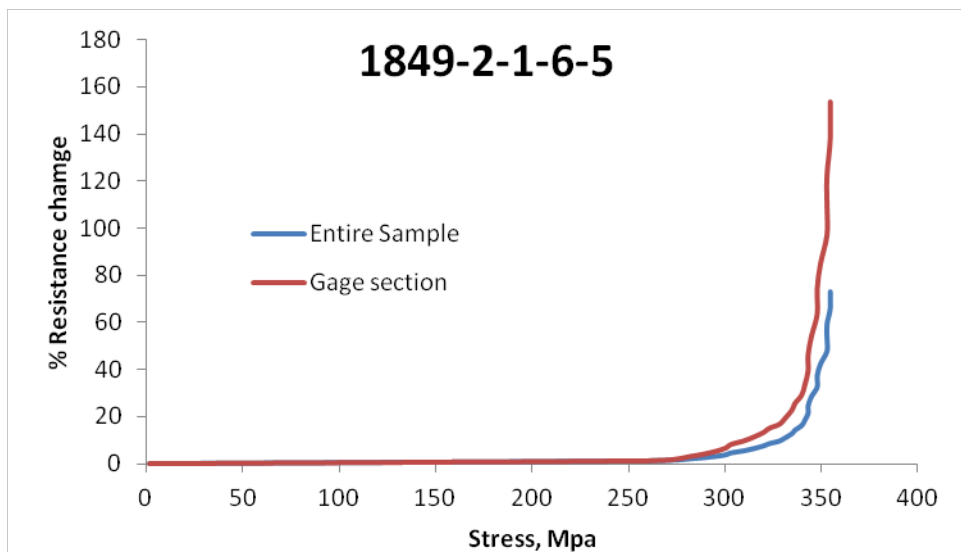
**HiPerComp Gen 2 – 2D prepreg  
laminate Hi-Nic-S,  $V_f \sim 0.26$ ,  
symmetric, balanced, 8 ply**

**0/90, +45/-45, +20/-70 Laminates  
Room temperature**

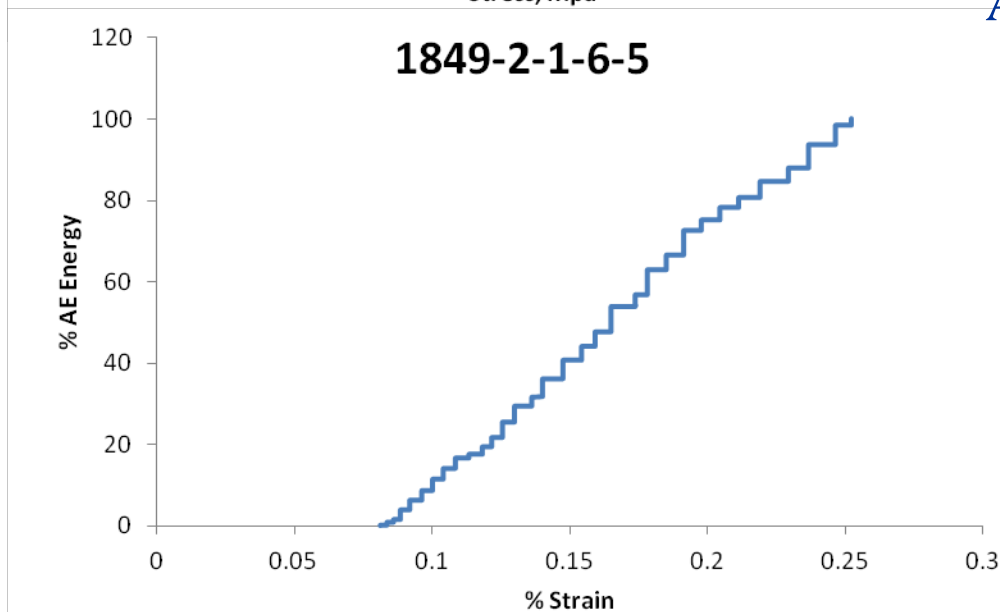




# Acoustic Emission and Electrical Resistivity Data



Craig Smith-  
Data utilized in modeling  
effort to understand damage  
accumulation – PhD thesis U.  
Akron





### Tensile Properties As-Received GE Gen-2 SiC/SiC Composites (Symmetric, Unbalanced, 6Ply, 0/90 laminates)

Specimen#	Test Temperature	DFL Stress	DFL Strain	Modulus	UTS	UTS
	<sup>o</sup> C	MPa	%	GPa	MPa	%
1849-02-001-6-2	25	261	0.09	295	351	0.22
1849-02-001-6-6	25	259	0.09	288	359	0.26
1849-02-001-6-3	25	174	0.06	304	364	0.28
1849-02-001-6-5	25	266	0.10	280	353	0.26
Average		240	0.08	292	357	0.25
SD		44	0.02	10	6	0.03
1849-02-001-6-1	1315	200	0.09	217	305	0.16
1849-02-001-6-8	1315	199	0.09	218	304	0.16
1849-02-001-6-4	1315	245	0.11	214	300	0.15
Average		215	0.10	216	303	0.16
SD		26	0.01	2	2	0.00

### Tensile Properties As-Received GE (Gen-2) SiC/SiC Composites (Symmetric, Balanced, 8Ply, (-20/+70) laminates)

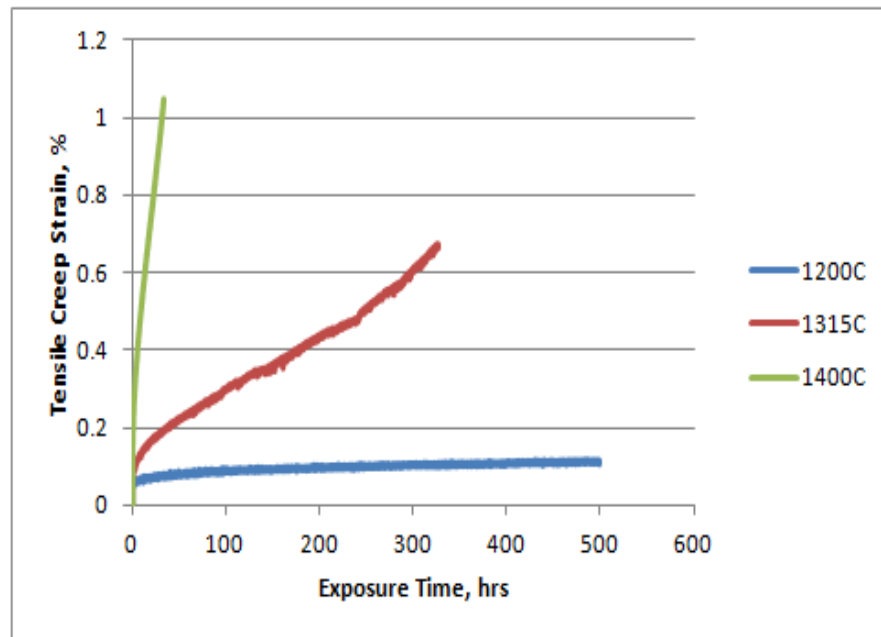
Specimen#	Test Temperature	DFL Stress	DFL Strain	Modulus	UTS	UTS
	<sup>o</sup> C	MPa	%	GPa	MPa	%
1847-01-049-4	25	199	0.07	277	245	0.25
1847-01-048-5	25	158	0.06	249	213	0.09

Note: DFL-Deviation from linearity; UTS-Ultimate tensile stress or strain; SD-Standard deviation

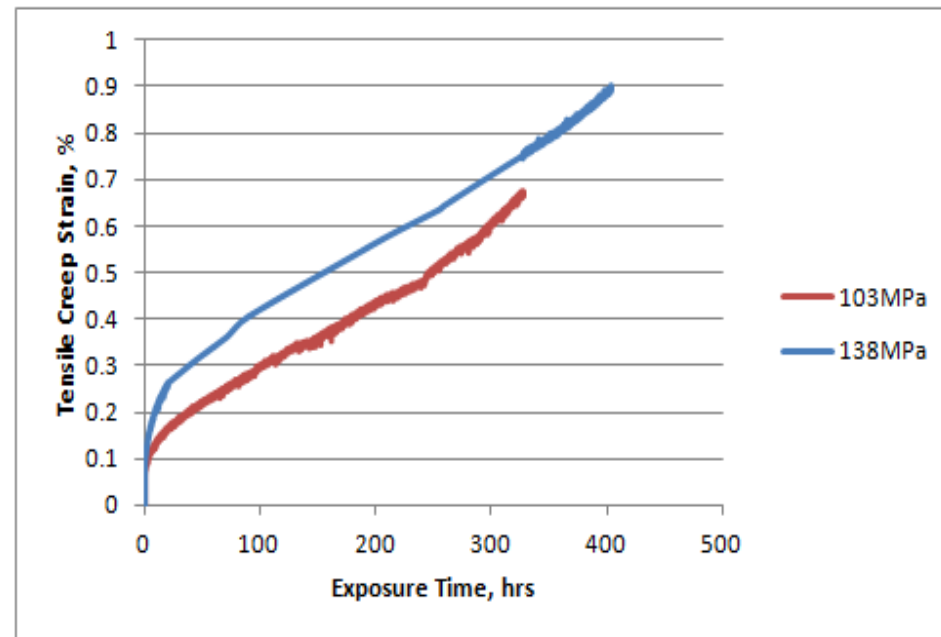
### Tensile Properties of As-Received GE (Gen-2) SiC/SiC Composites (Symmetric, Balanced, 8Ply, (+45/-45) laminates)

1847-01-051-02-L10	25	176	0.07	270	227	0.10
1849-01-001-02-L7	1315	141	0.07	193	223	0.14

## Influence of Temperature on Creep Behavior ( $V_f \sim 0.26$ ) Tested in Air at 103MPa (Symmetric, Balanced, 8Ply, 0/90 laminates)

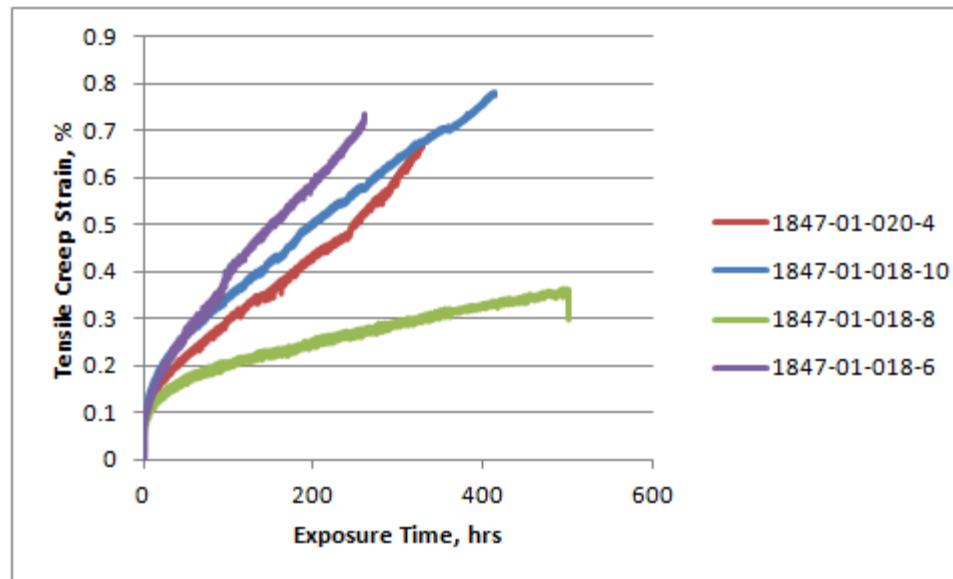


## Influence of Stress on Creep Behavior ( $V_f \sim 0.26$ ) Tested at 1315°C in Air at 103MPa (Symmetric, Balanced, 8Ply, 0/90 laminates)





**Specimen to Specimen Variation in Creep Behavior of  
GE (Gen-2) Prepreg SiC/SiC Composites ( $V_f \sim 0.26$ )  
Tested at 1315°C in Air at 103MPa  
(Symmetric, Balanced, 8Ply, 0/90 laminates)**



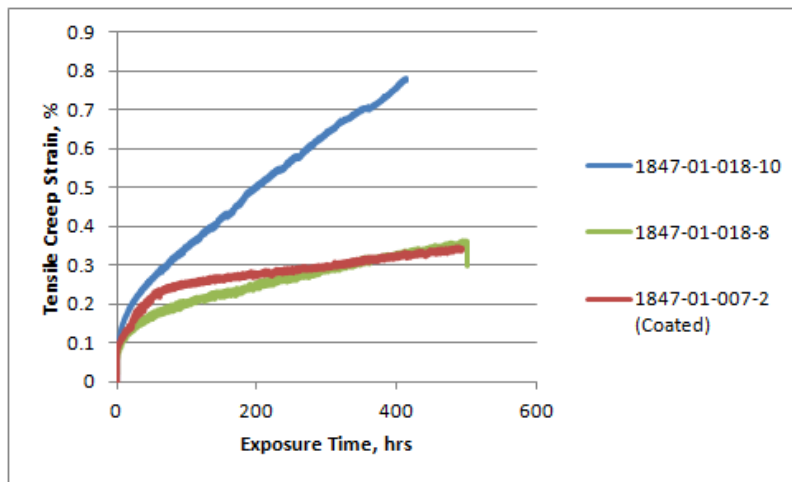
Note: Significant variations in creep behavior seen from specimen to specimen. Some specimens appear to be cracked during creep deformation.



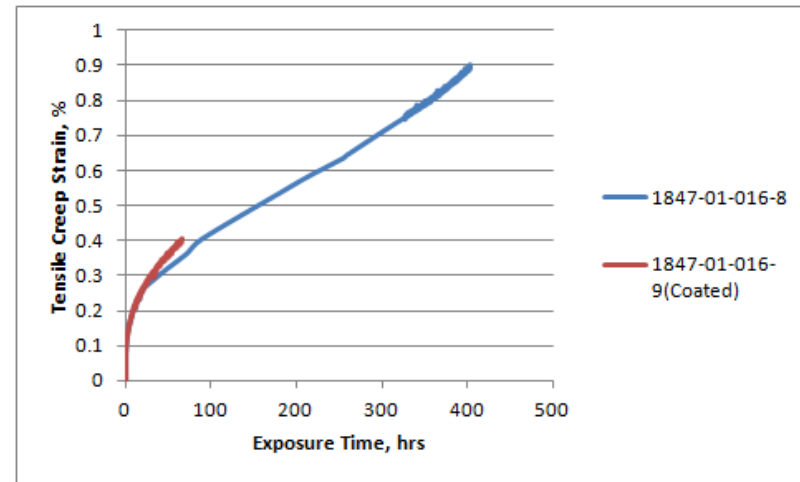


## Influence of EBC on Creep Behavior of GE (Gen-2) Prepreg SiC/SiC Composites ( $V_f \sim 0.26$ ) Tested at 1315°C in Air (Symmetric, Balanced, 8Ply, 0/90 laminates)

103 MPa

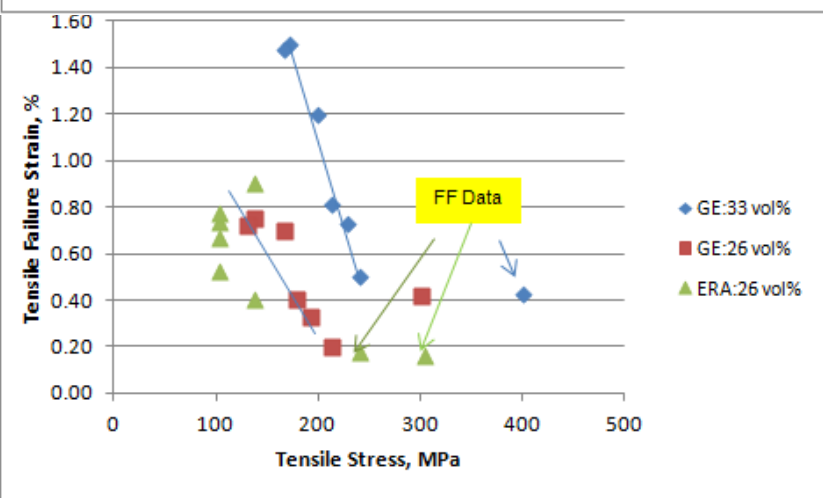
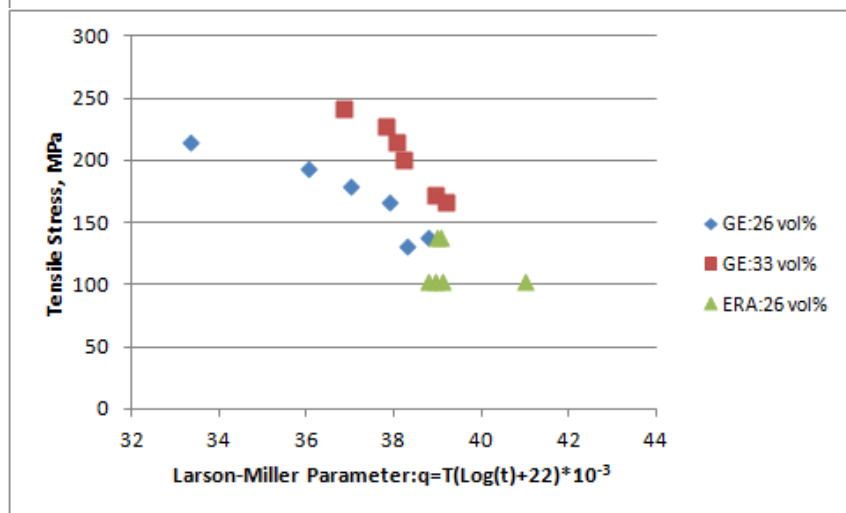
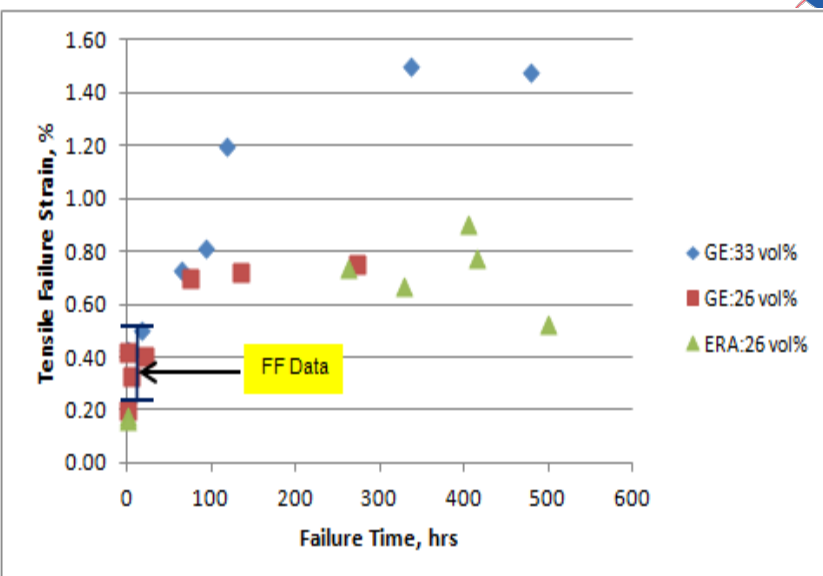
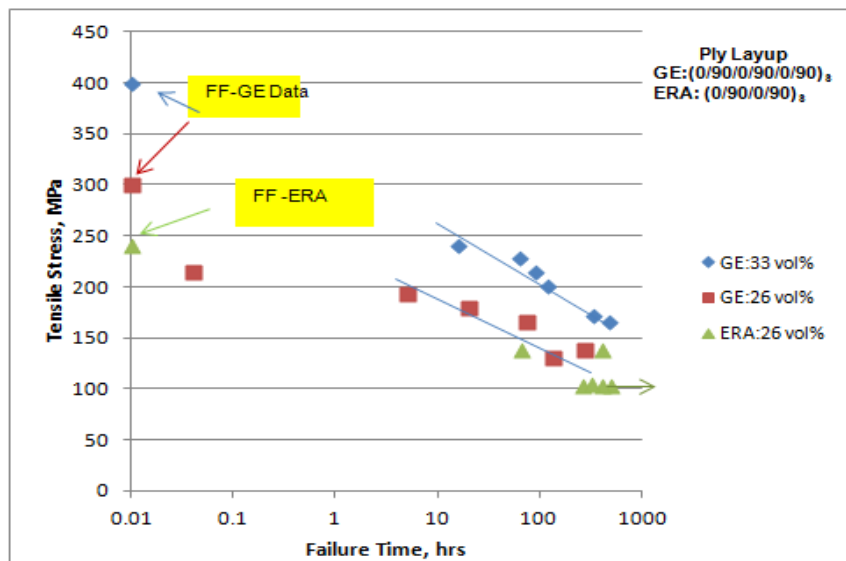


138 MPa



Note: Surface coating has no significant influence on creep behavior or creep rate.

## Tensile Creep and Fast Fracture (FF) Data at 1315°C in Air



Note: Fiber volume percentages reflect total fiber content which includes both axial and transverse fibers.

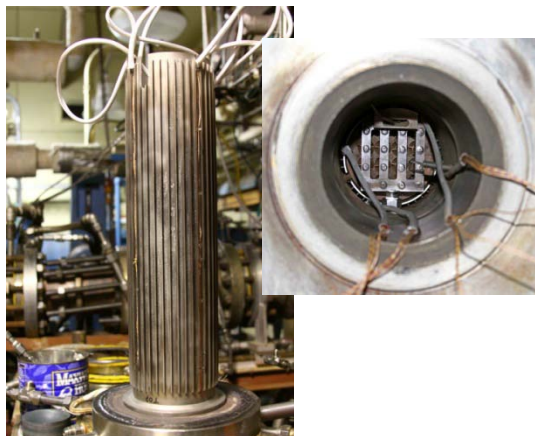
GE 33 and 26vol% composites: Gen-2 matrix. From Dunn

Note: Creep rupture strains are much greater than the FF strains.

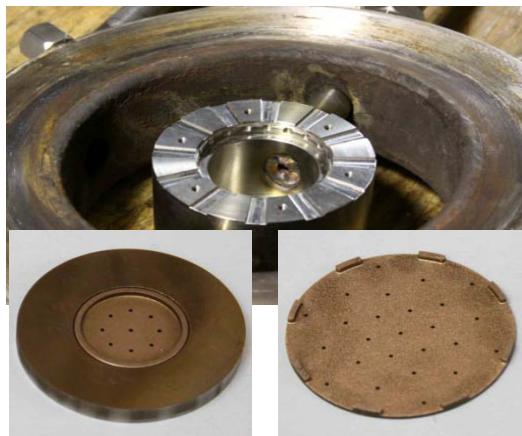
# ERA CMC Combustor Liner

## Realistic Test Conditions

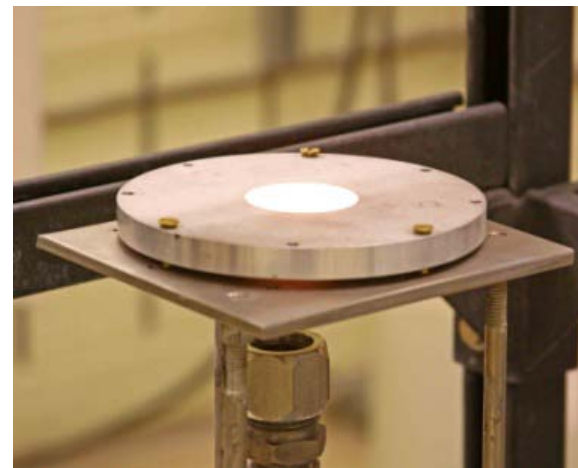
- Test fixtures prepared for CMC and CMC-EBC combustor testing: addressing not only uniform high heat flux testing environments, but also hot spot environments encountered in CMC combustor liners; Biaxial stress will also be emphasized



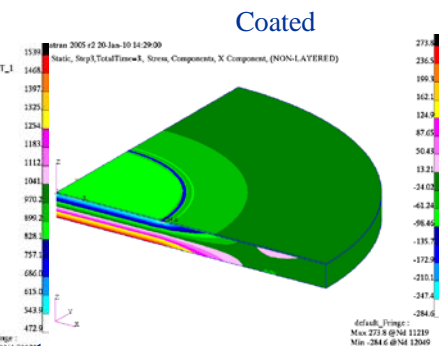
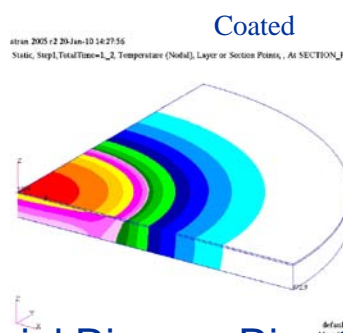
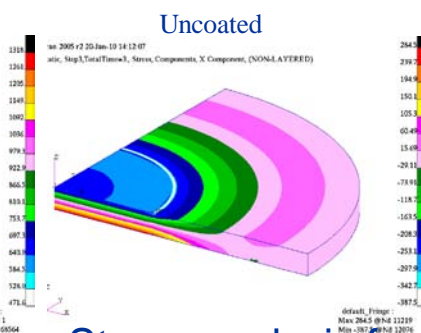
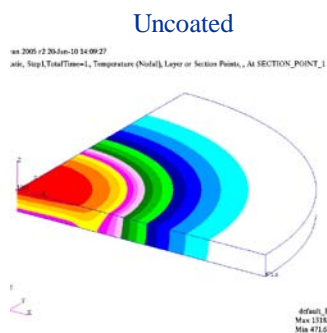
High pressure burner rig metallic liner instrumented and prepared for testing to determine the temperature distributions after the fuel injector



High heat flux cooled CMC-EBC disc coupon fixture designed and machined : shower heads for simulated engine impingement cooling and also providing film cooling sources with high pressures



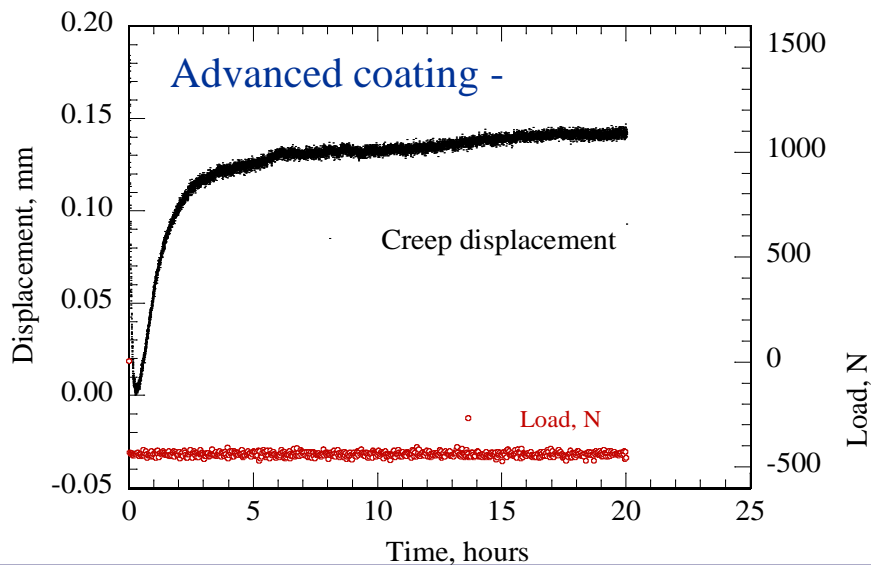
Laser high heat flux cooled CMC-EBC disc coupon test to accommodate 2'' CMC disc tests: component conditions



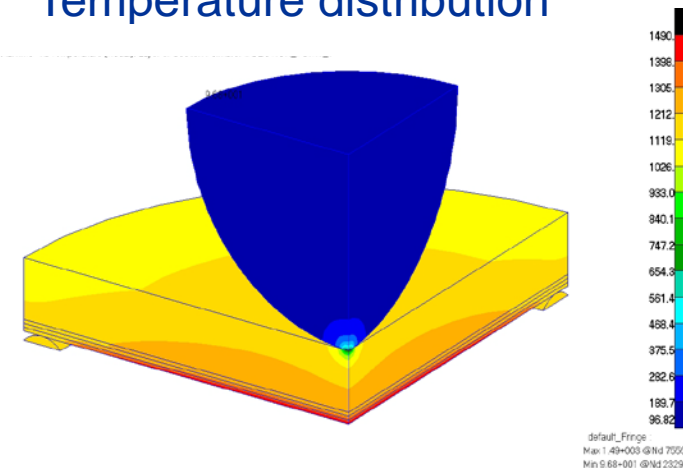
Stress analysis for biaxial Ring-on-Ring tests

## Creep rupture tests

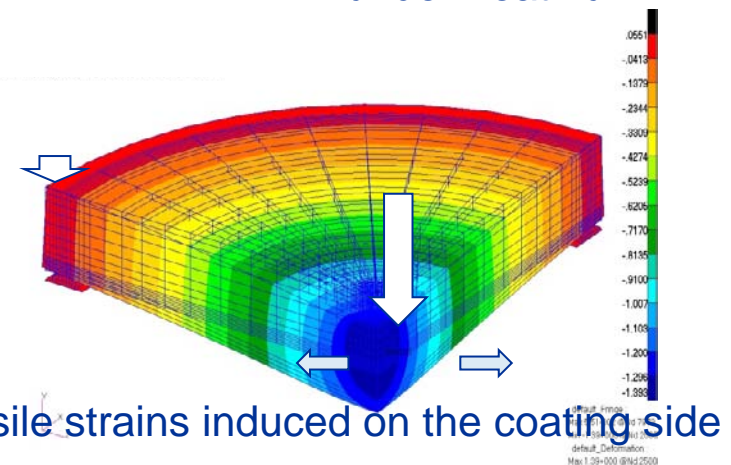
- Tensile creep rupture tests fully developed, demonstrated long term test durability.
- Ball-on-ring tests are being used to generate initial creep results
- Creep performance is being developed for baseline materials



## Temperature distribution



## Axial total displacement under heat flux

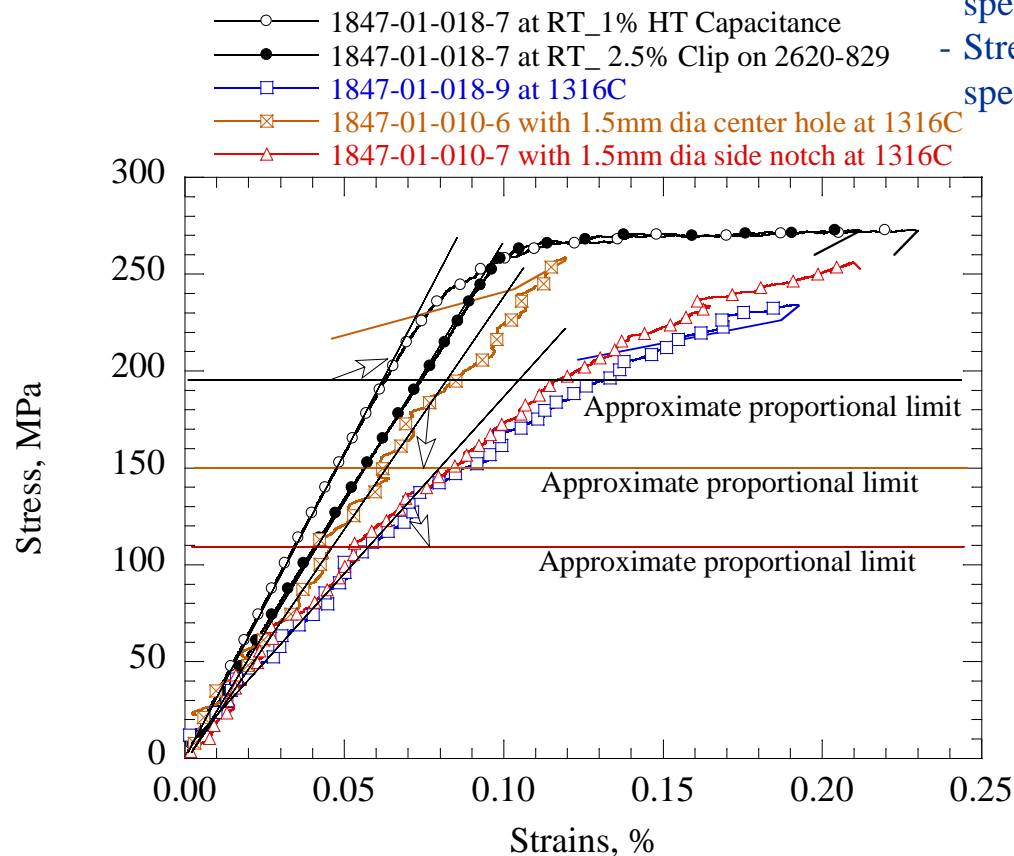


## Tensile strains induced on the coating side

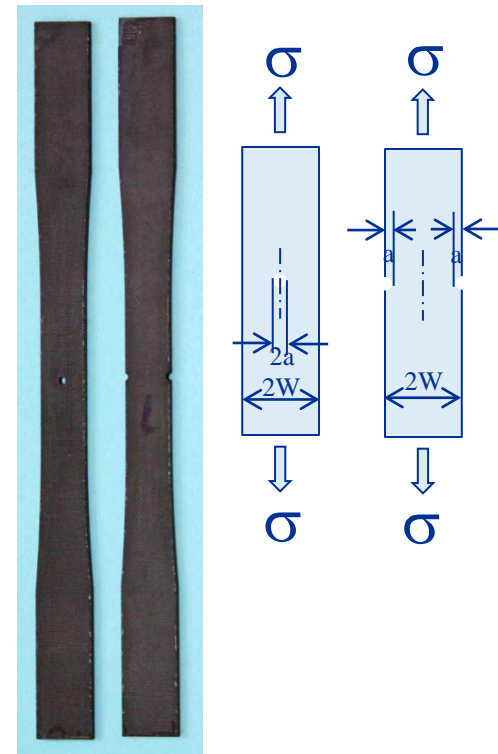
# Notch Sensitivity Tests of Gen II CMC - NASA

- No obvious strength degradation in the presence of the center hole and notches (1.5 diameter,  $a/W=0.15$ );
- Ultimate tensile strength at 1316°C is 247.2+/-10.9 MPa (data from three panels);
- Ultimate tensile strength at Room temperature (RT) is 274.4+/-2.5 MPa (two panels);
- Some strength variations from panel to panel observed (strength standard deviation is 10 MPa among Panels vs. within panels ~2MPa)

Panels 1847-01-018 and 1847-01-010



- Stress concentration factor  $k_t$  2.76 at specimen mid plane);
- Stress concentration factor 2.33  $k_t$  at specimen surface





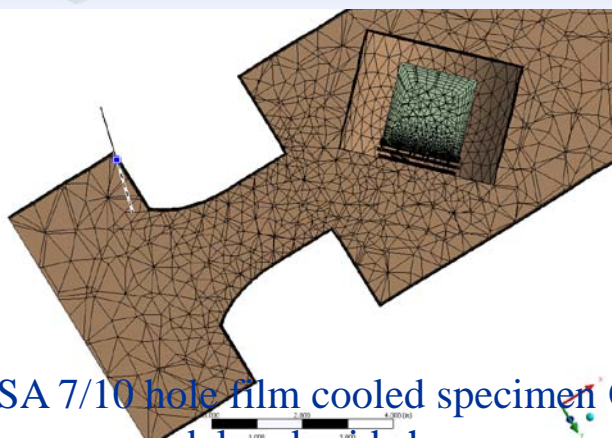
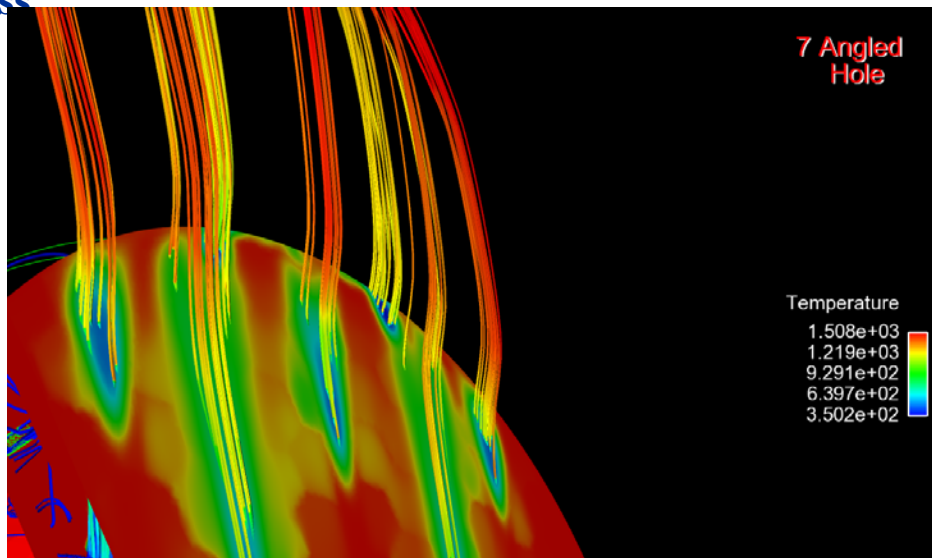
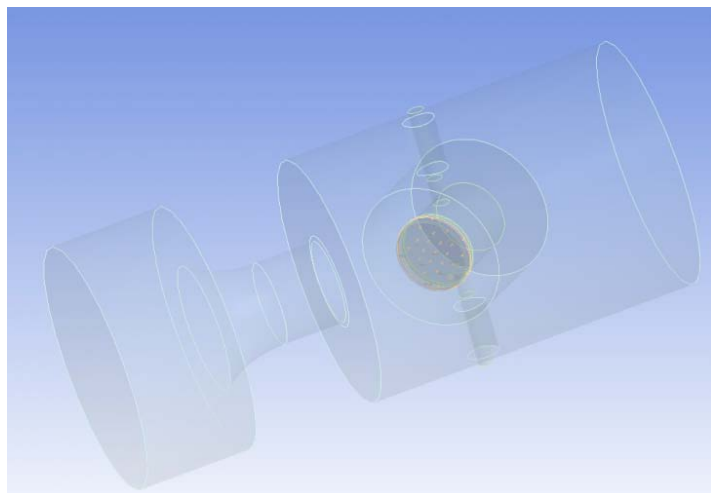


# The Environmental Barrier Coating Development for SiC/SiC CMC Combustors – Initiation CFD Analysis of Film Cooled Recession

## Specimens

### CFD Film Cooling Modeling

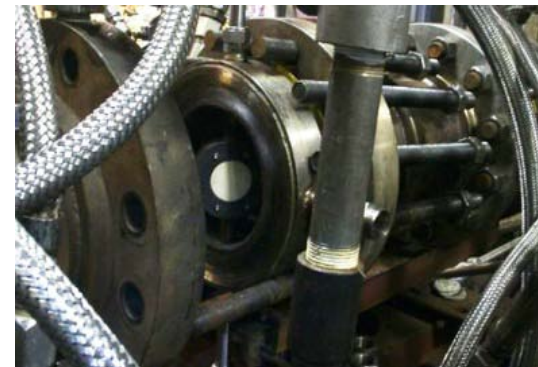
- 3D CFD finished for both NASA 7, 10, 17 hole specimens and GE film cooled specimens
- Initial 7-hole specimen validation in progress



NASA 7/10 hole film cooled specimen CFD model and grid shown



7 hole film cooled specimen on test rig

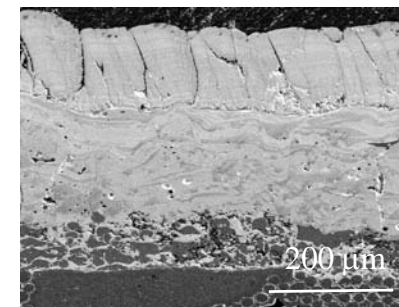
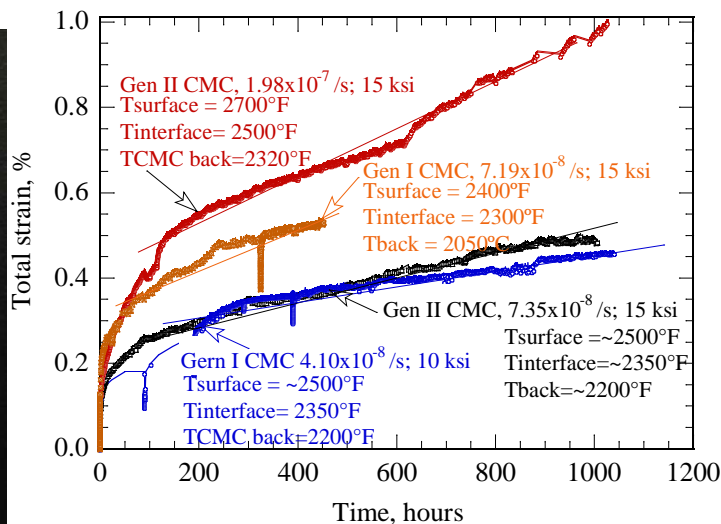
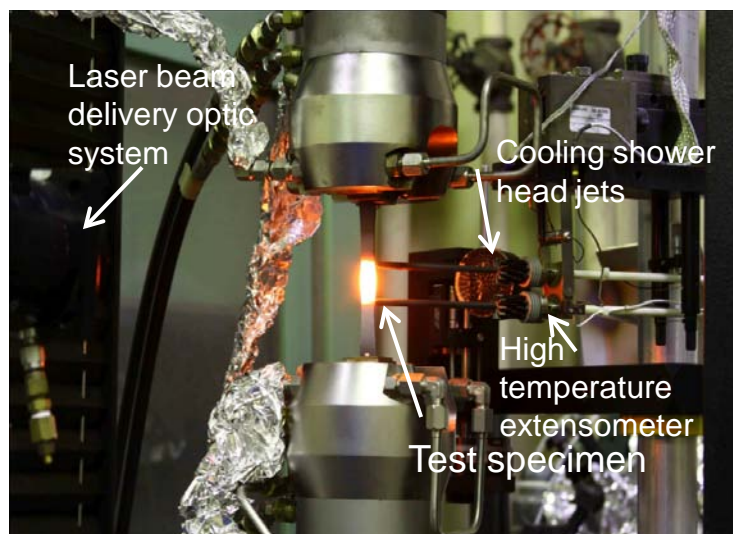


Specimen testing configurations

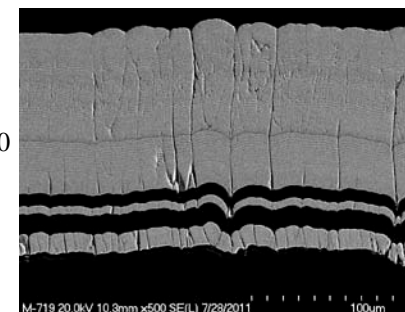
# Multicomponent Turbine Environmental Barrier Coatings

## Successfully Demonstrated Heat-Flux Tensile Creep Rupture Durability

- Advanced high stability multi-component hafnia-rare earth-silicate based environmental barrier coatings successfully tested 1000 hr creep rupture at 2700°F (1482°C) – one of many ebc examined



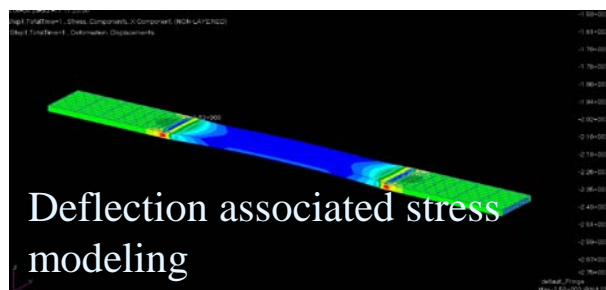
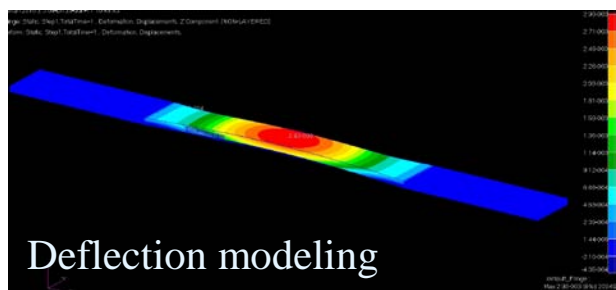
Hybrid EBC with Si-HfO<sub>2</sub> bond coat



NASA ND8 EB-PVD EBC



Turbine coating tensile specimen



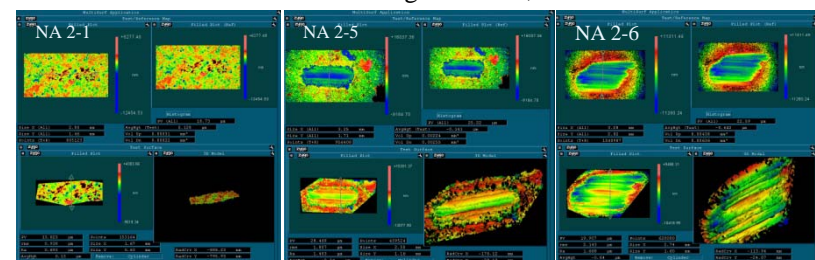
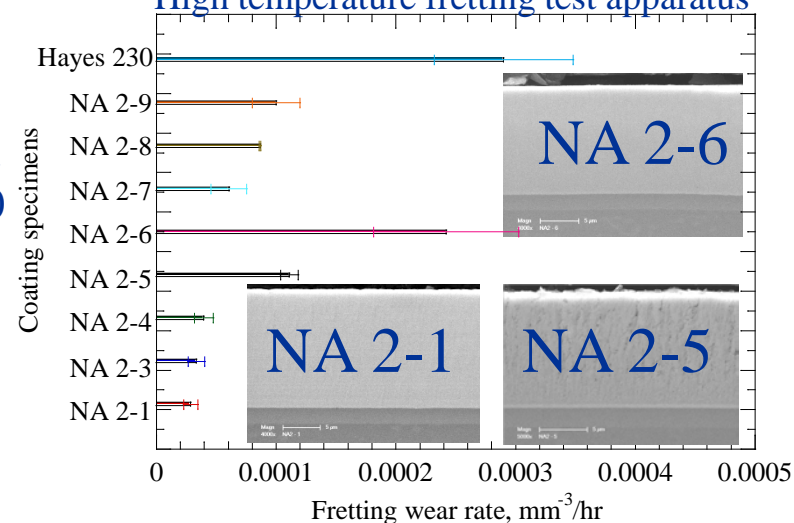
Modeling of Heat-Flux Tensile Creep testing completed

## CMC - Metal Component Integration – Development of Fretting Wear Resistant Coatings for SiC/SiC CMC Combustor

- Problem:** The incorporation of SiC/SiC CMC combustors into turbine engines requires the development of fretting wear resistant coatings. The high hardness CMC can cause extensive wear failure of metal components under high temperature and high cycle contact loading.
- Objective:** Develop fretting wear resistant coatings for CMC Combustor integration.
- Approach:** Advanced Fretting coatings were processed and evaluated for improved high temperature fretting wear at 80 Hz, 300g contact loading at 800C and with a  $\text{Si}_3\text{N}_4$  pin. A DoE processing matrix was used to optimize compositions and coating architectures.
- Results:** The coating achieved 3-10 times fretting wear resistance as compared to the Haynes 230 alloys. Optimum coating structure and compositions were achieved to endure high hardness and toughness, contact fatigue resistance
- Significance:** The technology will enable reliable CMC combustor applications.



High temperature fretting test apparatus



Fretting wear surfaces of NA 2-1, NA 2-6 and NA 2-5





## Realistic Environment Testing for CMC Combustor Liner Subcomponents

**ERA - CMC Combustor liner goal – 60 atm, 2700 F**

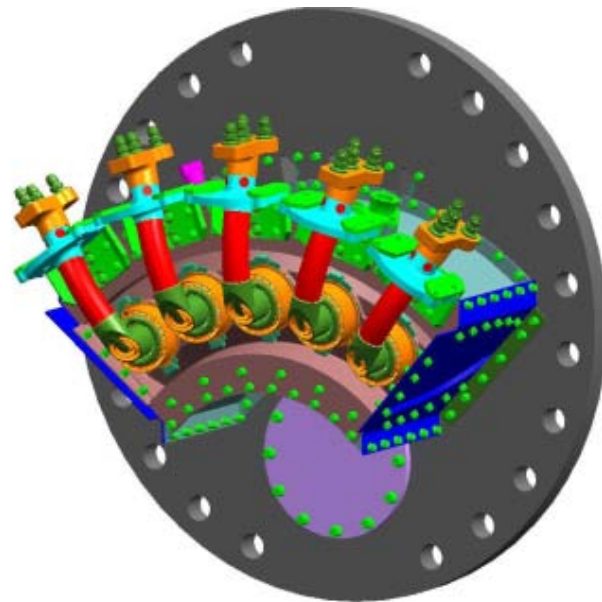
### Two Approaches -

High Pressure Burner Rig (HPBR) – CMC liners added to rig

- 16 atm
- Hundreds of hours – piggy back testing in other programs - \$

Advanced Subsonic Combustion Rig (ASCR) - CMC sector test

- 60 atm
- mass flow rates to 38 lbm/s
- Short testing times - \$\$\$\$

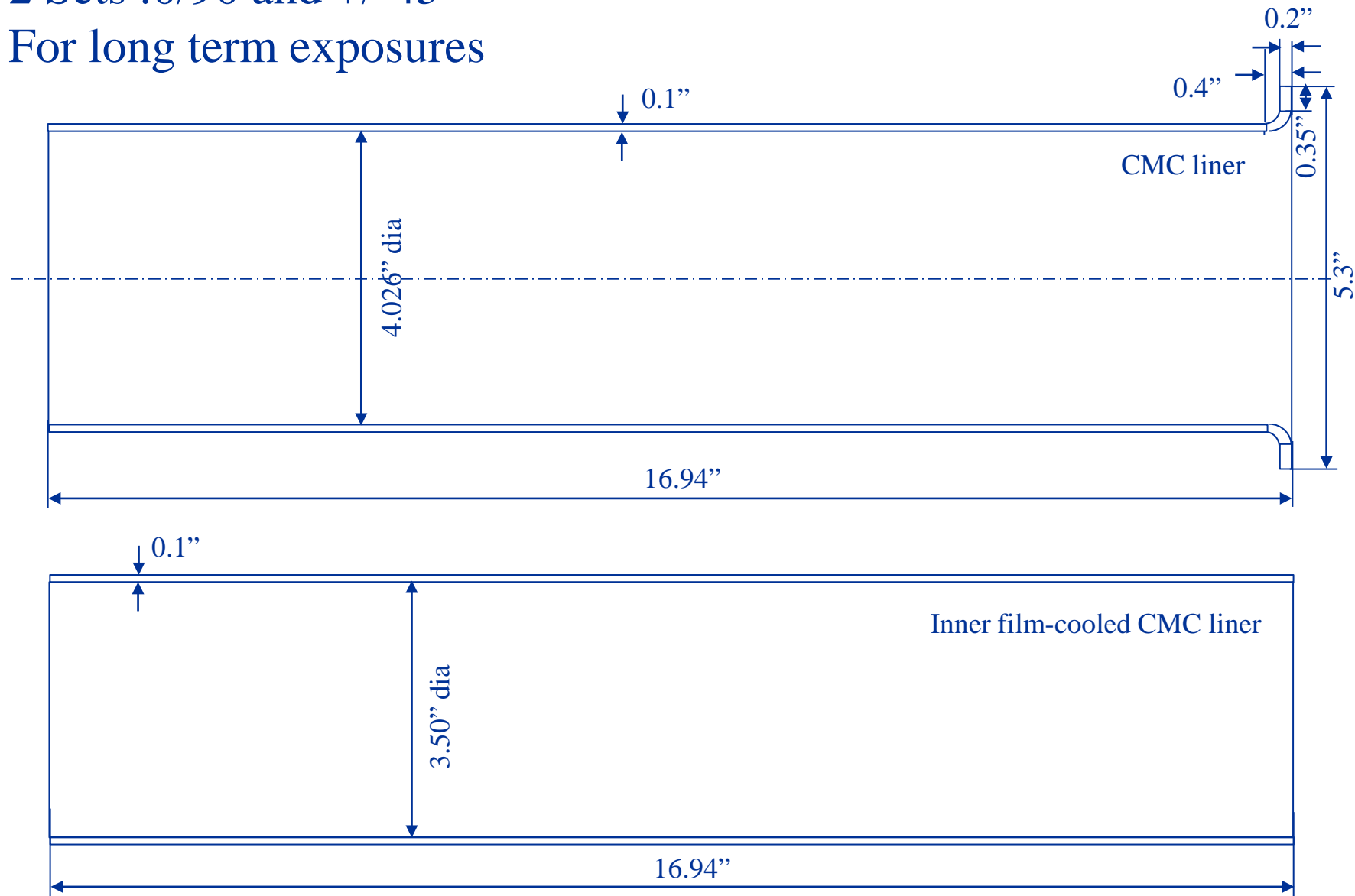


## ERA SiC/SiC CMC Combustor Liner Test Articles – NASA

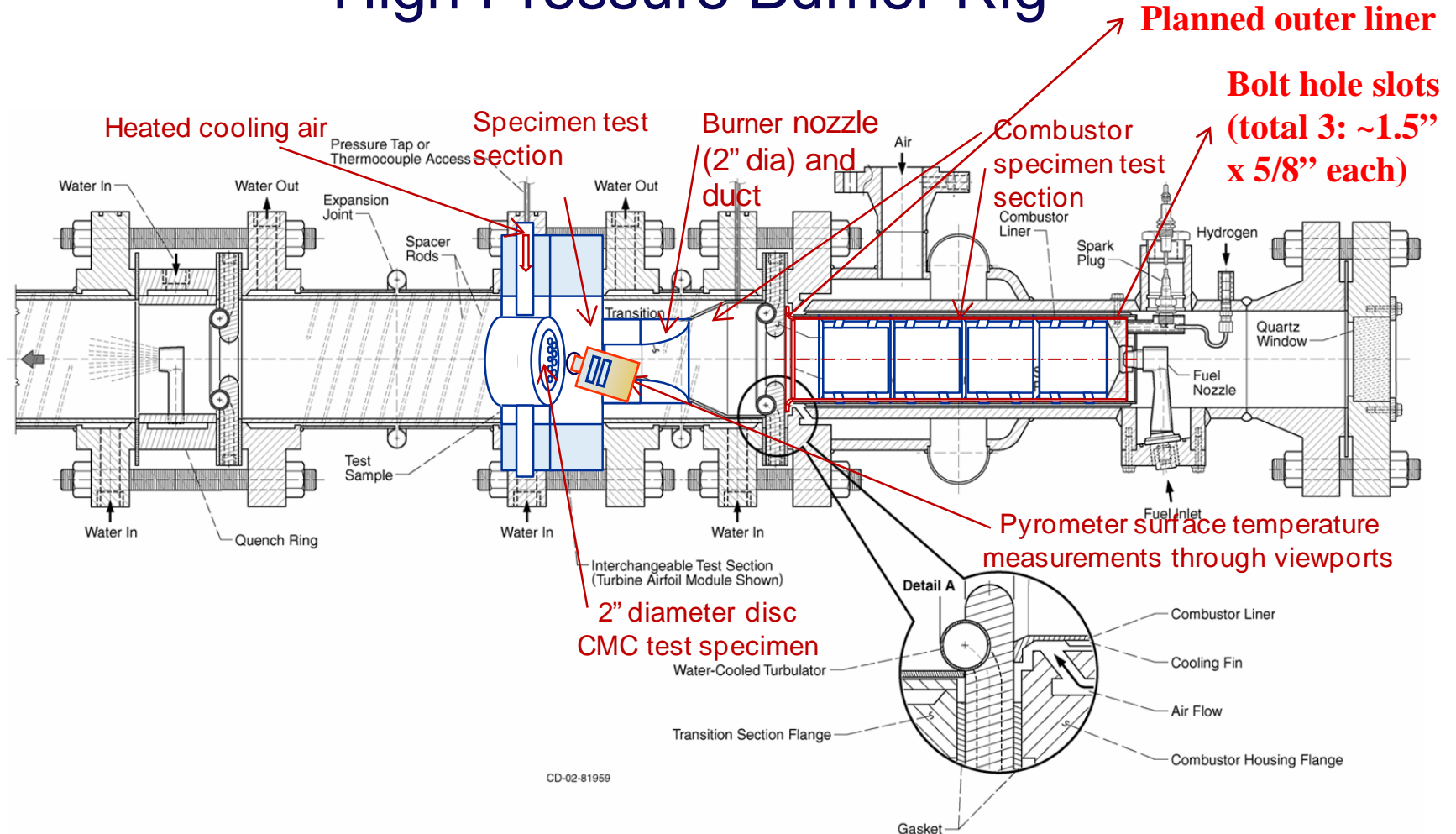


2 Sets :0/90 and +/-45 High Pressure Burner Rig

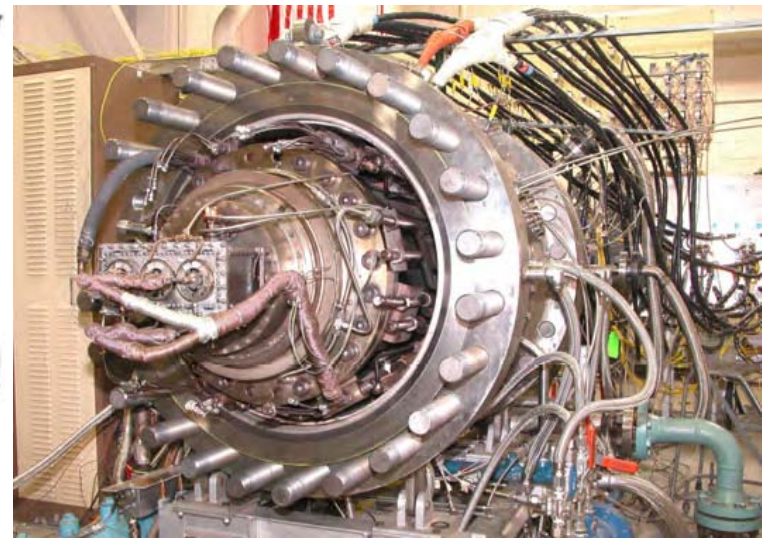
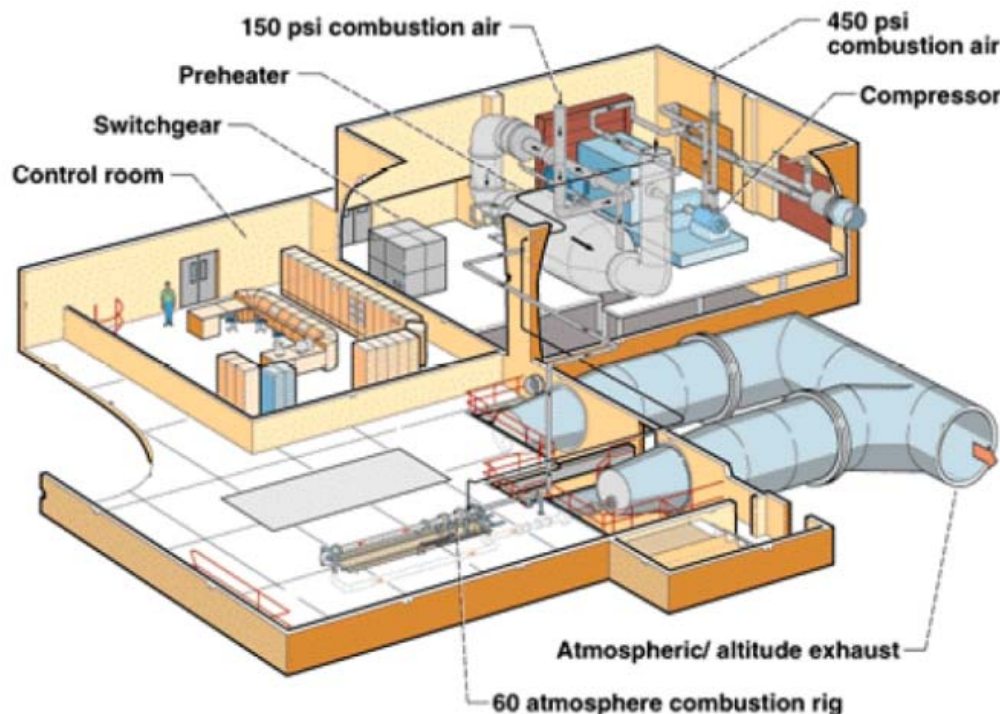
For long term exposures



# High Pressure Burner Rig



# Low Emissions Combustor Testing: Advanced Subsonic Combustion Rig (ASCR) A high-pressure, high temperature combustion rig



- Supports research on multiple fuel injector test hardware for large aircraft engine development,
- Full-scale annular combustor development for regional aircraft engines
- Fuel flexible capability being added: Can switch on the fly between two fuel supplies and blend fuels
- Flametube and sector configurations
  - Sector configuration is a “shell-in-shell”
  - Outer shell has optical access
- Conditions: Inlet T to 1300 F and p to 60 atm, mass flow rates to 38 lbm/s



# Summary For NASA ERA CMC Combustor Liner Task

- 3 year effort concludes this year with potential follow on for continued durability of CMC subcomponents/coupons pending selection of combustor technology for demonstration.
- Initial coupon durability testing will be concluded
  - NASA determined property test results similar to GE published results
  - Fiber dominated properties
  - Warping for off-axis. Zero's could not be fabricated
- Subcomponents for HPBR to arrive 1/12. Integration into HPBR will permit piggybacked testing for extended hours to compliment short duration testing in ASCR (100-200 hours).
- Advanced Environmental Barrier Coating development including non Si-bond coats for use at temperature 2700-2800 F or more. CMAS modeling initiated.
- Fretting coating found to greatly extend wear life at 800 C
- Temperature capability of advanced high temperature piezoelectric devices for fuel modulation pushed from 250C to 400 C